RADCOM TECHNICAL FEATURE

Spread Spectrum in Action

The first of a two part article

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SPREAD SPECTRUM techniques are becoming increasingly common in today's radio communication products – they are incorporated in proposals for the latest cellular telephone systems and radio-based computer local area networks. Until quite recently the major Spread Spectrum modulation formats – frequency hopping and direct sequence – were only found in radio systems destined for use by the military and certain government departments. To begin with, I will attempt to demystify the subject and highlight the possibilities for the Amateur Radio Service. [This raises a number of licensing issues. More on this next month – *Ed*].

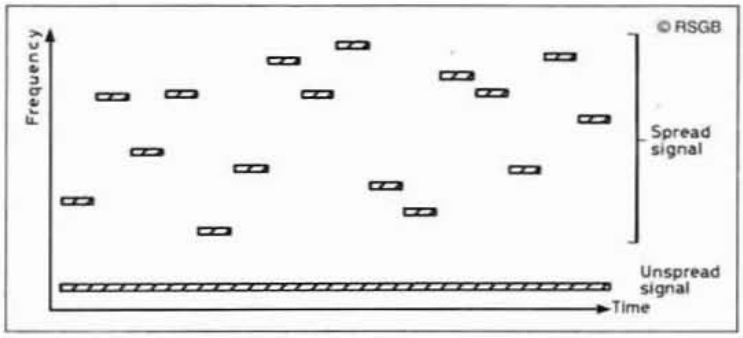


Fig 1: Example of the frequency hopping spectrum.

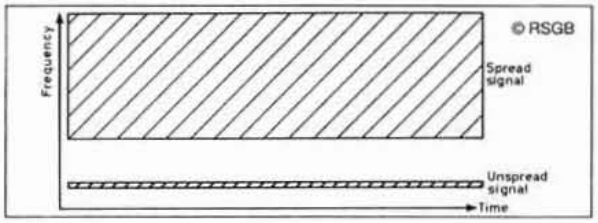


Fig 2: Frequency spectrum of a direct sequence tranmission.

WHAT IS SPREAD SPECTRUM?

MOST RADIO USERS, whether professional or amateur, are accustomed to minimising the radio frequency bandwidth they use in transmitting their signals. As a result there has been a move from double sideband to SSB transmission and an increase in data transmission techniques which utilise very narrow bandwidths. It is easy to visualise the advantages of a narrower bandwidth – more users can be accommodated in the same band and redundant sidebands (as in DSB) can be eliminated, permitting greater efficiency. The resulting narrower bandwidth reduces the noise (natural or man-made) at the receiver, thereby improving the signal to noise ratio. However, bandwidth expansion systems (such as wideband FM), benefit from an improved signal to noise ratio due to the modulation and demodulation process.

Spread spectrum systems use considerably larger bandwidths than conventional narrowband techniques to transmit the same information. Two criteria [1] for a Spread Spectrum system are that:

a) The transmitted bandwidth is much greater than the bandwidth or rate of the information being sent.
b) Something other than the modulation being sent determines the resulting transmitted radio frequency bandwidth.

The two major techniques used in such systems are frequency hopping (fh) and direct sequence (ds). Of the two, frequency hopping is perhaps the easiest to visualise.

CAUGHT ON THE HOP

IN A FREQUENCY HOPPING system the frequency or channel in use is changed rapidly. The transmitter hops from channel to channel in a pre-determined but pseudo-random sequence (see **Fig 1**). The receiver has an identical list of channels to use (the 'hop set') and an identical pseudo-random sequence generator to that of the transmitter. A synchronising circuit in the receiver ensures that the pseudo-random code generator in the receiver synchronises to the one in the transmitter.

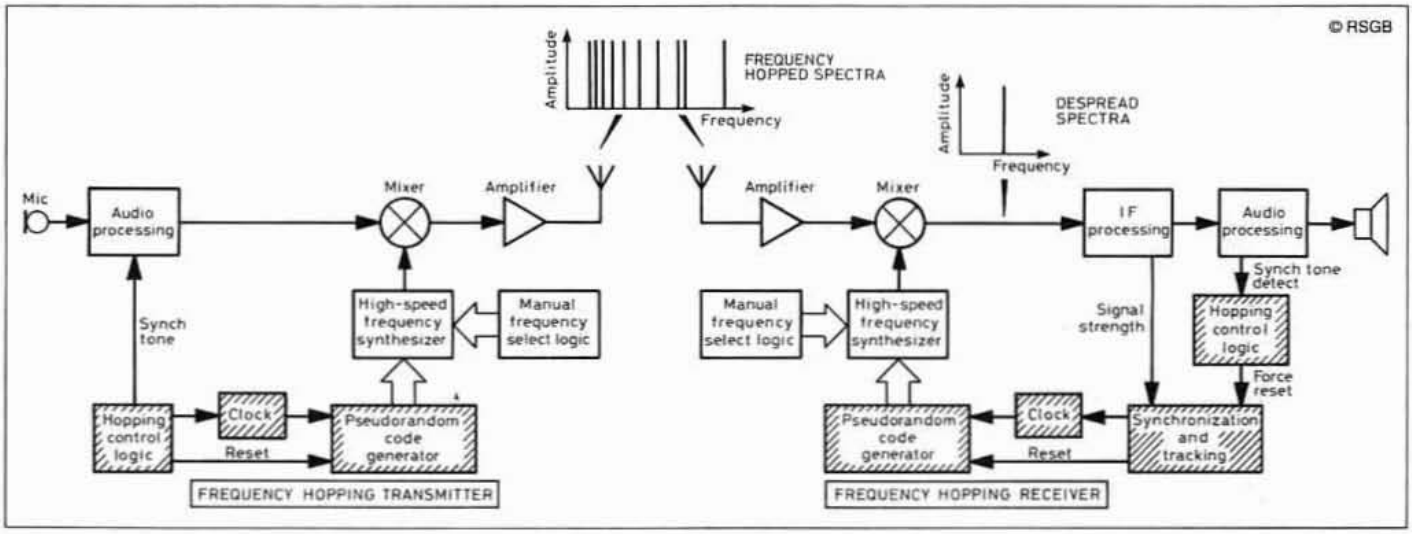


Fig 3: The block diagram shows how the frequency hopping receiver is a near mirror image of its associated transmitter.

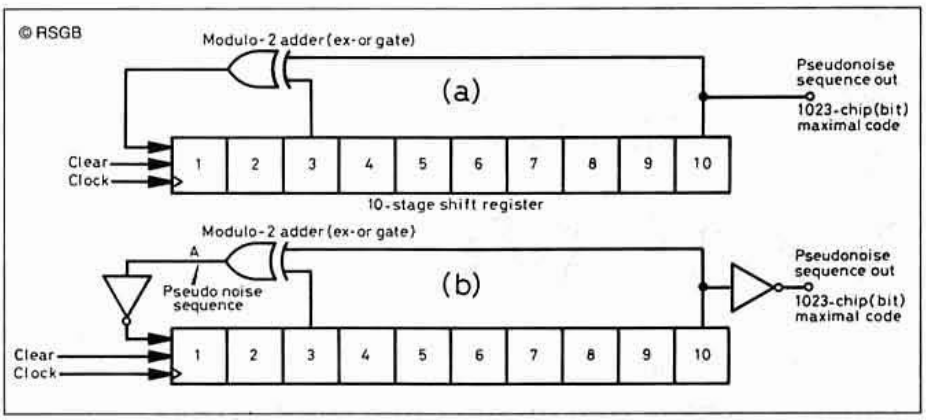


Fig 4: Pseudo-random sequence generator (a). The circuit at (b) avoids all-zero lock-up condition.

When the transmitter and receiver are synchronised the user is unaware that they are rapidly changing frequency. However should the receiver not be synchronised to the transmitter or a conventional receiver is used, nothing will be heard unless the transmitter hops onto the receiver's tuned frequency.

As a frequency hopping transmitter typically hops between tens and thousands of frequencies per second (the hop rate), the time it stays on a particular channel (the dwell time) is very short and as a result the signal would appear as a burst of interference.

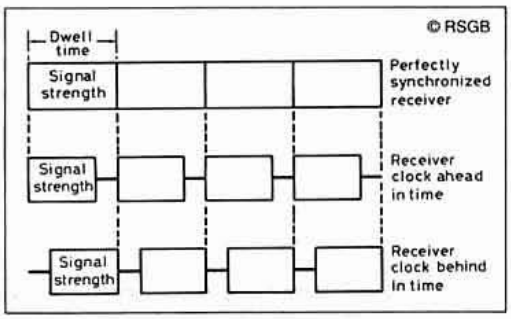


Fig 5: Synchronisation of the receiver results in uniform signal strength during the dwell time.

This can be likened to radio users operating to a rigorous schedule and operating only on particular frequencies at predetermined times. Such a system would use clocks synchronised to (say) GMT. Anyone wishing to join the net must have a list of frequencies to use and the time to use them, as well as a synchronised clock. Loss of any of these items will prevent communications and the same is true of a frequency hopping system.

DIRECT SEQUENCE ALTERNATIVE

THE OTHER MAJOR Spread Spectrum technique is known as direct sequence or pseudo-noise. In this technique a pseudo-random code phase shift keys the carrier, increasing its bandwidth (**Fig 2**). This is known as spectrum spreading. The receiver 'despreads' this wideband signal by using an identical pseudo-random code synchronised to that in the transmitter. As with the frequency hopper, the receiver must utilise a circuit to adjust its clock rate so that the receiver's pseudo-random code is at the same point in the code as the transmitter. A tracking circuit is necessary to maintain synchronism once it has been attained.

This brings us to a summary of the major advantages of the system. There must be major advantages in using Spread Spectrum, otherwise no one would utilise these techniques. It is obvious from the above that Spread Spectrum systems and particularly their receivers are considerably more complex than their narrowband counterparts.

MAJOR ADVANTAGES

THE MAJOR ADVANTAGES of Spread Spectrum can be summarised as follows:

a) Interference rejection.
b) Code division multiple access for multiple use of the same frequency.
c) Low power spectral density.
d) High resolution ranging.
e) Selective addressing.
f) Message privacy.

Spread Spectrum systems provide these attributes by virtue of their 'coded' carriers. The ability of these systems to reject interference, whether unintentional or deliberate jamming, together with their low power spectral density (ie Watts per Hertz) compared with a conventional narrowband transmitter, hastened their development by the military. They provided jam resistant, low probability of intercept (LPI) communication systems. In fact an early system was used during WWII to permit secure communication between Roosevelt and Churchill, [2]. As more information on Spread Spectrum techniques has come into the public domain there has been a rapid increase in civilian applications. The characteristics of Spread Spectrum are best examined after the techniques of spreading and despreading have been discussed.

FREQUENCY HOPPERS

A SPREAD SPECTRUM system can use conventional modulation such as FM, AM or their derivatives to modulate the carrier. Analogue modulation is most frequently found in frequency hoppers as FM voice or FSK data. FM is used rather than amplitude modulation as this ensures a constant power output rather than the varying power envelope produced by AM. A varying envelope signal reduces the covertness of the transmission (ie increases the probability of detection and recognition of the signal) which is naturally of great importance to the military user.

A frequency hopping radio has basically the same design as a normal transceiver (see **Fig 3**). However a few extra circuits (shaded in the diagram) are required. Most transceivers produced today use either phase-locked loop or a direct digital synthesizer [of course many now use both – *Ed*] to permit the users to select many operating frequencies without the complexity of a bank of crystals. The synthesizer of a frequency hopping radio is controlled by a circuit which selects a frequency according to either a pseudo-random sequence generator or a look-up table driven by a pseudo-random generator.

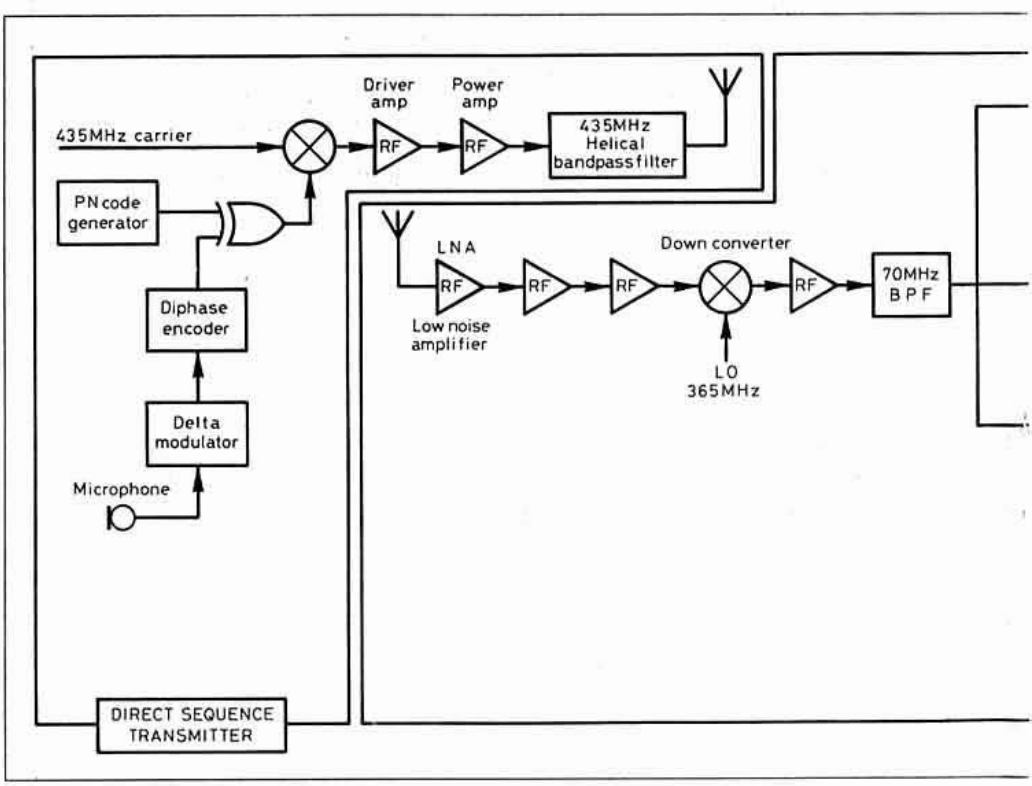


Fig 8: The Rx tracks the incoming transmission by using three IF channels in the despreading path.

In either case frequency selection is arranged such that the radio will hop from frequency to frequency in a pre-determined yet pseudo-random manner. The pseudo-random sequence generator is controlled by a very accurate timebase (usually a hi-stability quartz crystal oscillator) which determines the hop rate and consequently the dwell time.

SYNCHRONISED HOPPING

SO NOW WE HAVE a radio which has a frequency synthesizer capable of very rapidly changing frequency without spurious operation (not a trivial function!) and a pseudo-random code generator which determines the frequency to be used. The receiver needs to follow the transmitter's rapid hopping from one channel to another. The circuitry for the frequency synthesizer and pseudo-random generator are duplicated in the receiver.

We have to ensure that the transmitter and receiver start on the same point in the hop sequence and remain synchronised, such that on each hop the receiver and transmitter are tuned to the same frequency. Once the Tx and Rx are synchronised a 'tracking' circuit in the receiver is brought into operation to ensure synchronism is maintained. This ensures that the receiver clock tracks any frequency change or drift in the transmitter clock frequency.

How is synchronization between transmitter and receiver initially achieved? Firstly, we have the problem of ensuring that the pseudo-random code generators are both starting from the same point in their code sequence (which determines the frequency for communication) and secondly that the receiver and transmitter clock oscillator are of the same frequency and phase. The pseudo-random generator is usually configured from a shift register and a number of exclusive-OR (EXOR) logic gates (see **Fig 4**). The shift register can be reset by a logic level such that all its outputs are forced to a preset logic level. After this reset or clear command the pseudo-random code generator can produce its code sequence from a defined state.

In a commnly used synchronization technique, a synchronization signal (an audio tone or a digital sequence) is sent on a control or 'home' frequency. When this signal is received all hopping radios in the net have their pseudo-random generators and code clocks reset simultaneously. Thus each synthesizer will be tuned to the same frequency determined by the pseudo-random code generators and their clocks will cycle through the pseudo-random hop sequence in unison. The clocks in the transceiver need to be accurate and stable so that they do not rapidly lose synchronization with each other.

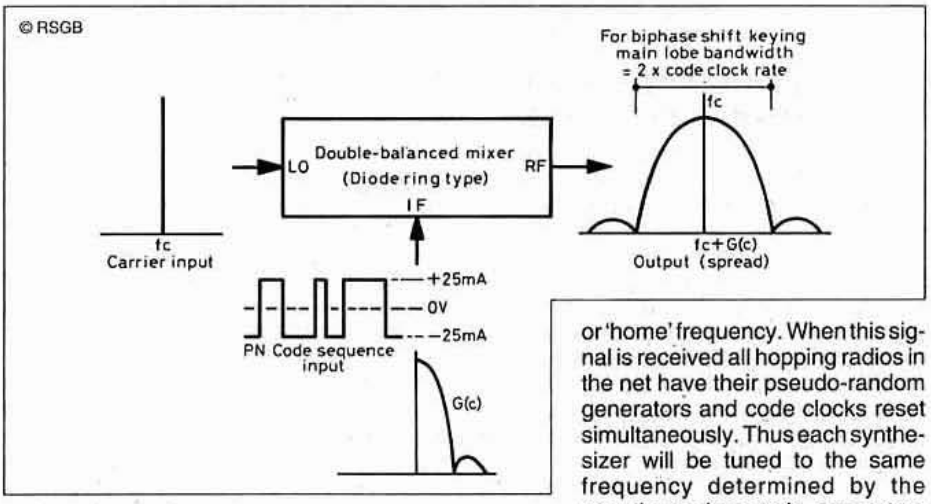


Fig 6: Direct sequence modulation using a double-balanced diode ring mixer.

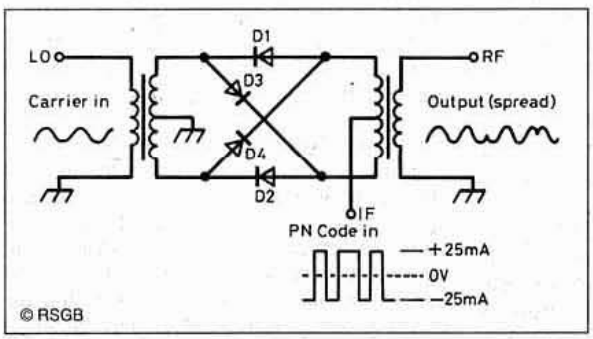
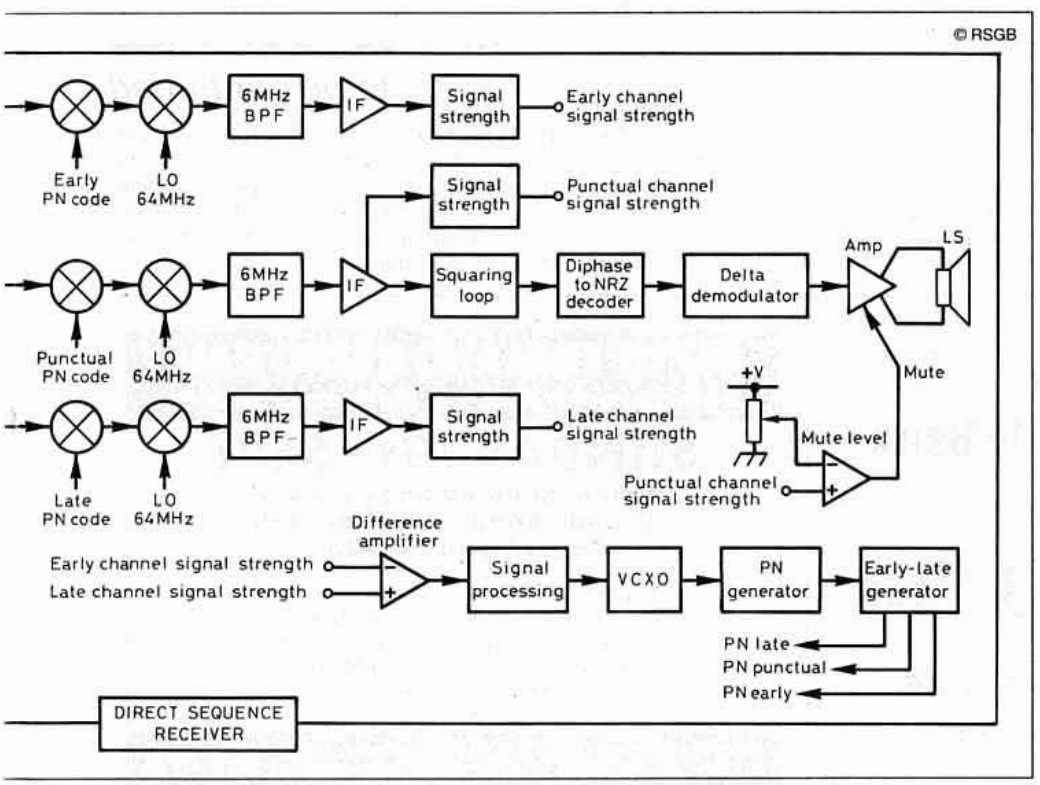


Fig 7: The mixer output is a series of symmetrical sidebands.

For hop rates in the order of tens to hundreds of hops per second, high stability quartz crystal oscillators can be used. The tracking circuit compares the signal strength of the dehopped (despread) signal over the dwell time. If the receiver is exactly synchronized (see **Fig 5**) then the signal strength is constant in amplitude over the whole of the dwell time. If the receiver clock is ahead of the transmitter (ie the receiver retunes to the next frequency in the hop set before the transmitter does) then the signal strength will be high then low over the dwell time. The opposite is true if the Rx clock is slower than that in the TX.

Thus by comparing the signal strength at the receiver over the dwell time a control loop can be made to either advance or retard the receiver's pseudo-random clock. This in turn ensures that the receiver stays in synchronism with the transmitter.

If the signal path is obscured for a short period, it is possible that with high stability code clocks in the transmitter and receiver the system could remain synchronised. If synchronism is lost however, the users must force their system to the home or control channel and re-synchronise using the synchronization tone-sequence.



CHOOSING YOUR CLOCK

IT IS POSSIBLE to use clock signals obtained from an external source which can be easily disseminated to all users – this avoids the need for individual clock circuits in each frequency hopping transceiver. Such accurate clocks exist in the signals from Navigational Satellites such as the GPS/Navstar system and in the colour-burst synchronization signals in television signals [3].

Of course, the transmissions from a standard frequency and time station such as MSF at Rugby could also be used. With an external clock system the advantage of no longer needing clock and tracking circuitry is coun-

tered by the need for an additional clock signal receiver for both the Rx and Tx.

DIRECT SEQUENCE (PSEUDO-NOISE) SPREAD SPECTRUM

A DIRECT SEQUENCE transmitter uses a pseudo-random sequence generator to phase shift a carrier (see **Fig 6**). Typically, a direct sequence system will use a double-balanced mixer (DBM) to switch a carrier between 0° and 180° (0 and Pi radians). This is also known as biphase-shift keying (BPSK) or sometimes phase reversal keying (PRK). Unlike a frequency hopping transmitter where the pseudo-random sequence commands a synthesizer to change frequency, the direct sequence signal is directly generated by the pseudo-random sequence.

In the generation of a double sideband signal with a double balanced mixer, the audio signal is applied to the IF (intermediate frequency) port. The carrier to be modulated is connected to the LO (local oscillator) input, and the amplitude modulated carrier extracted from the RF (radio frequency) port.

DIGITAL MODULATION

WHEN A DBM IS USED as a biphase modulator the digital modulating mode is applied to the IF port. Rather than the analogue sinusoidal signal in the previous DSB example the digital pseudo-random code switches between a negative and positive voltage. This alternately sources and sinks current as shown in **Fig 7**. The result is that diodes D1, D2, D3, D4 alternatively switch on and off causing a 180° phase reversal in the carrier signal. The output spectra is not like the DSB case with a pair of sidebands (upper and lower). Instead it is a series of symmetrical sidebands which have a $((\sin x)/x)^2$ distribution due to the many frequency components of the pseudo-random sequence.

As the spreading code has a pseudo-random character the occurrence of a particular frequency component is pseudo-random in time and the direct sequence output appears and sounds like noise when demodulated on a narrowband receiver. As a result direct sequence spread spectrum is also known as pseudo-noise modulation. If we assume that the receiver's pseudo-random code is synchronised to the transmitter's then the despreading process is identical to the spreading process.

CODE MODIFICATION

WITH ANALOGUE MODULATION on a direct sequence carrier anyone can recover the modulation without previous knowledge of the pseudo-random spreading code either by simply tuning to one of the spectral components, if close to the transmitter, or by using a system that squares the direct sequence signal. This produces a pure carrier at twice the centre frequency of the direct sequence signal (the mathematically minded reader is referred to [4]). A technique frequently used to modulate direct sequence signals with data is known as code modification.

With code modification the data or digitised speech is EXORed with the pseudo-random spreading code. This has the effect of inverting the code if the data is '1' or leaving the pseudo-random spread code unaffected if it is 'O'. At the receiver the unmodified code despreads the direct sequence signal to produce a narrowband signal which is still biphase shift modulated but this time with the data or digitised speech. This signal can then be demodulated by a conventional biphase shift demodulator such as a squaring or Costas loop demodulator.

The recovered data can then be either output to the outside world or in the case of speech converted back into an analogue speech signal using a suitable D to A converter. Synchronization is achieved in a similar way to frequency hopping synchronization. A variable frequency clock in the receiver is set to run either slightly faster or slower than that in the transmitter. At a particular instant the faster (or slower) code in the receiver will match (correlate) with the transmitted pseudo-random sequence and the spread transmitted signal will be despread into a narrowband signal (containing the data).

DATA DECODING

THE SYSTEM WILL DETECT this synchronization and engage a tracking circuit to ensure that the receiver code clock tracks any frequency change in the transmitter's clock. One technique (delay-locked loop) uses three receiver intermediate frequency channels in the despreading path. An on-time or punctual pseudo-random code is used for signal recovery, but for tracking an advanced early code (ahead of the punctual code) and a retarded late code are utilised.

The early and late codes are each offset from the punctual code by a fraction of a code bit (chip). For optimum performance this offset is one half a chip. After the signal is despread the energies of the despread signals in the early and late channels are compared. If they are identical the receiver code clock is running at the same frequency as the code clock at the transmitter (neglecting doppler and propagation delay effects).

If more energy is detected in the late channel compared with the early one then the receiver code check is running too slow and must be advanced. This information is part of a control loop which either increases or decreases the frequency of the receiver's code clock – often a high stability voltage controlled crystal oscillator. **Fig 8** shows a typical implementation of a delay-locked loop receiver and a companion direct sequence transmitter.

REFERENCES

[1] *Spread Spectrum Systems Second Edition*, Robert C Dixon, Wiley Interscience, ISBN 0-471-88309-3.

[2] 'Cryptology and the Origins of Spread Spectrum', David Kahn, *IEEE Spectrum Magazine*, September 1984.

[3] 'Practical Spread-Spectrum: A Simple Clock Synchronization Scheme', André Kesteloot, N4ICK, *QEX*, October 1986 (Also in the *ARRL Spread Spectrum Sourcebook* p8.27 to 8.30).

[4] 'Appendix 4 – Multiplication of Direct Sequence Signals (p 390 & 391)', *Spread Spectrum Systems*, 2nd Edition, Robert C Dixon, Wiley Interscience.

A list of other useful publications for those interested in this form of communication will be included next month.

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. . . to be continued

NEXT MONTH: In the final part of this feature, James Vincent gives further details of the techniques used in Spread Spectrum transmissions. Also the results of trials carried out on the amateur bands with a practical communication system.

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RADCOM TECHNICAL FEATURE

Spread Spectrum in Action

the second of a two part article
by James A Vincent, BSc (Hons) C.Eng MIEE, G1PVZ

LAST MONTH, I explained the principles behind frequency hopping and direct sequence Spread Spectrum transmissions. Also the circuit elements required for a practical implementation.

Fig 9 is a spectrum analyser plot showing a Spread Spectrum signal and the associated despread spectrum. These plots were obtained from the first practical amateur direct sequence system used in the UK. The direct sequence system can use conventional analogue modulation such as amplitude or frequency modulation, but as discussed for frequency hopping this has disadvantages which are even more pronounced with a direct sequence signal.

INTERFERENCE REJECTION

AS HIGHLIGHTED EARLIER there are several advantages in using Spread Spectrum techniques, and one of the most important is interference rejection. As the carrier is spread over many megahertz of bandwidth the receiver has to 're-map' the bandwidth used for transmission down to a narrowband signal for subsequent filtering and demodulation. As can be seen from Figs 3 and 8 (last month) there is essentially little difference between the spreading and despreading circuitry on a Spread Spectrum transmitter and receiver (whether direct sequence or frequency hopping).

If a narrowband interfering signal is received on a direct sequence receiver the interference will be 'spread' over the spread bandwidth of the system. This is achieved by the biphase shift modulator, used to despread the wanted Spread Spectrum transmission as shown in **Fig 10**. This has the effect of diluting the power of the interfering signal over a wider bandwidth whilst the wanted Spread Spectrum signal is concentrated by despreading into a narrow bandwidth signal. Thus the interfering narrowband signal has less energy after the IF filtering to interfere with the wanted transmission.

For a frequency hopping system it is somewhat simpler to visualise the interference rejection properties. As a frequency hopper hops over many frequencies a narrowband signal will only cause interference should the frequency hopper hop onto that particular frequency. In other words the transmission would be jammed only if the hop set included that interfering frequency and then only for the dwell time of the frequency hopper. The greater the hop speed (ie the shorter the dwell time) and the greater the bandwidth the system can hop over, the less significant is the effect of narrowband interference.

PROCESS GAIN

WE WILL NOW CONSIDER a very important and fundamental concept in Spread Spectrum systems; process gain (Gp). The process gain indicates the gain or signal to noise (S/N) improvement exhibited by a Spread Spectrum system by nature of the spreading and despreading process. Process gain can be estimated by the following empirical relationship:

$$\text{Process gain} = Gp = \frac{BW_{RF}}{R_{info}}$$

$$\text{Process gain} = 10\log_{10}\left(\frac{BW_{RF}}{R_{info}}\right) \text{ dB}$$

Where BW_{RF} = 3dB bandwidth of transmitted Spread Spectrum signal (Hz), and

R_{info} = data rate of the information transmitted, in bits per second

For a direct sequence signal BW_{RF} is assumed to be equal to the 3dB bandwidth of the spectrum (which is 0.88 times the pseudo-random code clock rate for a biphase shift keyed direct sequence system). For a frequency hopping system BW_{RF} is equal to m times the channel bandwidth where m is the number of frequency channels available.

Although the process gain is directly related to the interference rejection properties a more indicative measure of how a Spread Spectrum system will perform in the face of interference is the jamming margin (Mj).

JAMMING MARGIN

THE PROCESS GAIN OF A system will always be greater than its jamming margin.

$$\text{Jamming Margin (Mj)} = Gp - [L_{system} + (S/N)_{OUT}] \text{ dB}$$

Where

L_{system} = system implementation losses, and

$(S/N)_{OUT}$ = signal to noise ratio at the information output.

A Spread Spectrum system with a 30dB process gain, a minimum required output S/N ratio of 10dB and system implementation loss of 3dB would have a jamming margin of 30 – 10 – 3dB, ie 17dB. The Spread Spectrum system in this example could not be expected to work in an environment with interference more than 17dB above the desired signal.

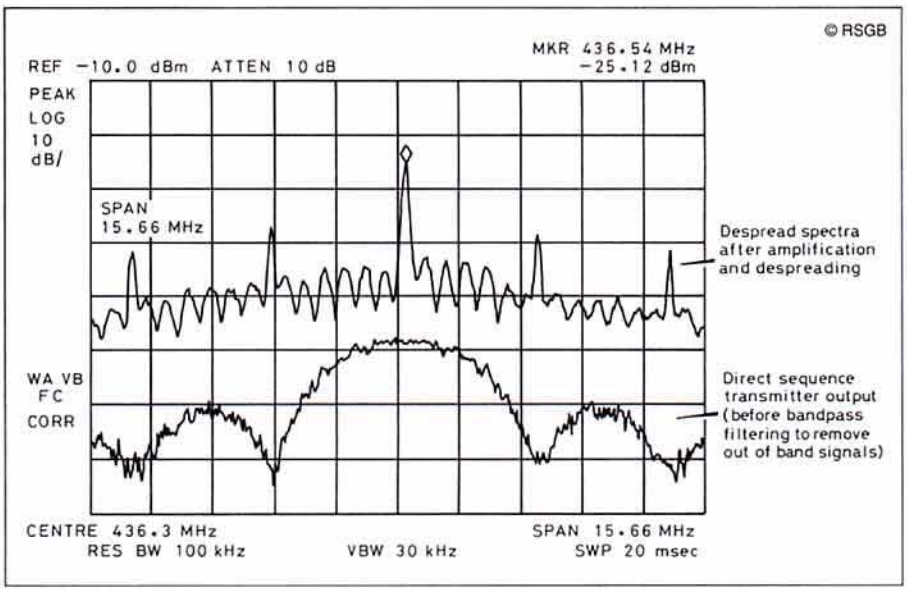

Fig 9: The transmitter output and despread spectra as displayed on a spectrum analyser.

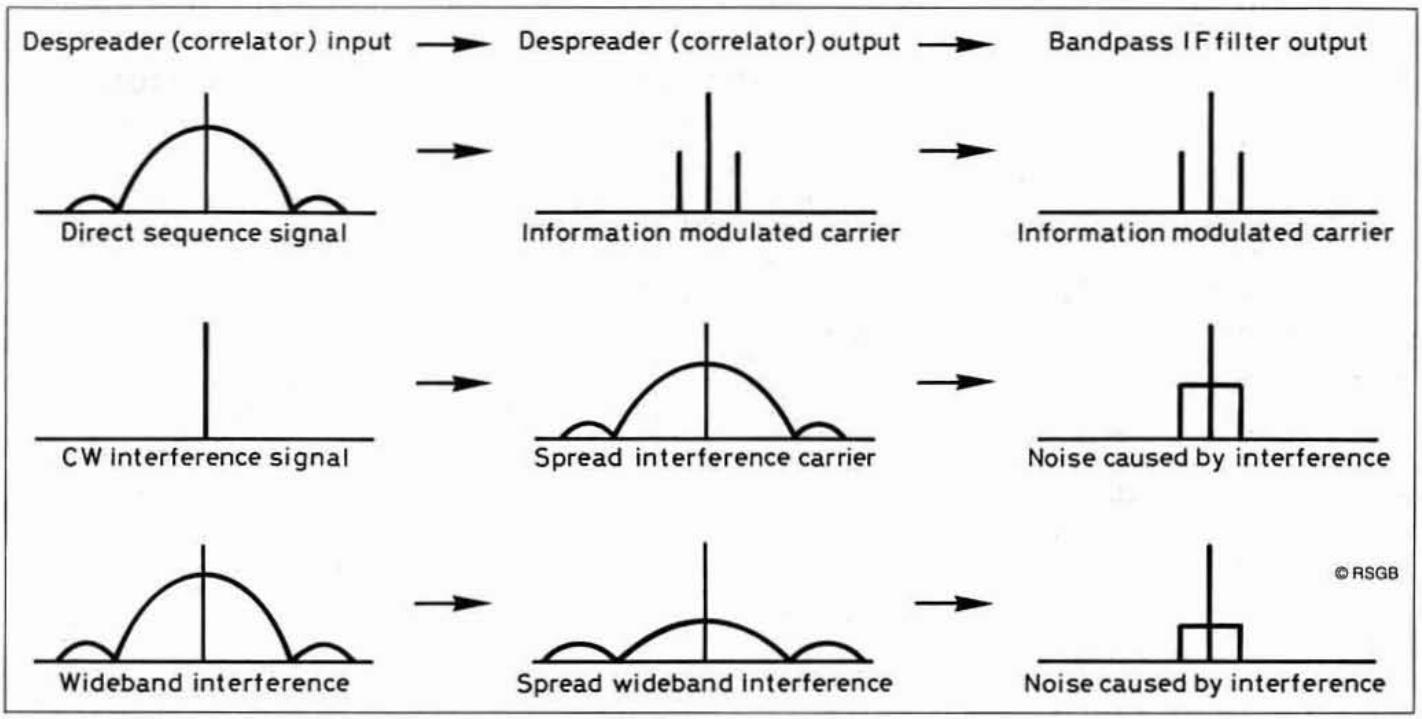

Fig 10: Effect of narrowband and wideband interference on a Spread Spectrum signal.

CODE DIVISION MULTIPLE ACCESS (CDMA)

AS ALL SPREAD SPECTRUM systems use a code to determine the transmitter's output, it is possible to have multiple usage of frequency and selective addressing by using different spreading codes for differing user groups. A Spread Spectrum receiver will see another Spread Spectrum signal as interference and reject it as it would a narrowband signal. However for a high degree of co-user rejection, spreading codes must be carefully chosen to minimise cross-correlation (See Appendix B). Cross-correlation is a measure of the 'match' between two different spreading codes. When there is only one transmitter and receiver the spreading codes are chosen such that the correlation is at a maximum when the two codes are in synchronization, that is the receiver and transmitter are both at the same point in the code sequence.

MATCHING USER CODES

WITH MULTIPLE USERS, multiple spreading codes will obviously be in use. Since a spreading pseudo-random code consists solely of binary '1's and 'O's there will be time in the code sequences where there will be a degree of matching or 'cross-correlation' between different user codes. This cross-correlation limits the number of users that can use the frequency at any one time.

It is possible to select mathematically, groups of spreading codes which work well together. Careful selection of spreading codes is essential for multiple use of frequencies whether they are used in direct sequence, frequency hopping or hybrid Spread Spectrum systems.

LOW POWER SPECTRAL DENSITY

BY NATURE OF THE 'SPREADING' process, the output power of the Spread Spectrum transmitter is spread over typically many megahertz of bandwidth. The spectral density is measured in how many watts of ratio frequency power are present per Hertz of bandwidth. Thus for a direct sequence transmitter of 1W output and a spread bandwidth of say 8MHz the power spectral density is:

$$\frac{1}{8{,}000{,}000}\ \text{Watts/Hz} = 125\text{nW/Hz}$$

For a conventional narrowband AM transmitter the power spectral density is around:

$$\frac{1}{6{,}000}\ \text{Watts/Hz} = 167\mu\text{W/Hz}$$

(around 1,300 times or 31dB greater)

The advantage to military users is that the signal strength apparent on a conventional narrowband receiver is very, very low and would probably not be recognised as a communications signal, hence the expression 'Low Probability of Intercept' (LPI) and 'Low Probability of Recognition' (LPR).

ADVANTAGES TO AMATEURS

FOR RADIO AMATEURS, the major advantage of the low power spectral density is the possibility of simultaneously using frequencies for both conventional narrowband and Spread Spectrum communications. The Spread Spectrum system rejects the narrowband communications as interference by nature of the process gain. The narrowband communications system would merely experience a reduction in their signal-to-noise ratios proportional to their proximity to the Spread Spectrum transmitter.

In the case of a frequency hopper a short interruption to the narrowband communication link would be apparent should the hopper hop onto the narrowband frequency in use. If this is not acceptable then the hop set could be selected so that discrete frequencies (eg repeater inputs) are excluded.

HIGH RESOLUTION RANGING

BY NATURE OF THEIR digitally coded carriers, Spread Spectrum systems particularly direct sequence techniques lend themselves to precise ranging. In fact the global positioning satellite (GPS – Navstar) system depends upon direct sequence modulation and high stability clocks to enable a user's receiver to determine its position and velocity in three dimensions over the vast majority of the earth's surface. The operation of GPS is not explained in this article as it has been exhaustively discussed elsewhere, [5], [6] and [7].

PRACTICAL SPREAD SPECTRUM

SINCE 1986 THE US Federal Communications Commission has permitted US radio amateurs to use Spread Spectrum techniques on amateur bands on or above 70cm. Much ground-breaking work has been carried out by US amateurs, in particular by members of AMRAD (The Amateur Radio Research and Development Corporation), a non-profit making international group of radio amateurs interested in advanced communication techniques.

During 1987, I built a Spread Spectrum demonstration system as a final year undergraduate project at Plymouth Polytechnic. It did not freely radiate and the synchronization and tracking circuit was not implemented as the transmitter and receiver circuits shared the same code generator. The system was built to examine the signal characteristics and jamming resistance afforded by direct sequence modulation.

THE US EXPERIENCE

WHEN IT WAS LEARNT that US radio amateurs were experimenting with Spread Spectrum, I approached the Radiocommunications Agency for permission to test such a system on a UK amateur band. The current UK amateur licence does not permit the use of

Spread Spectrum modulation. The agency staff were most helpful and after technical discussions, I was authorised to experiment on the 70cm allocation with a maximum output power of not more than 1 Watt EIRP.

Having gained this essential permission a design was constructed based upon the work of André Kesteloot, N4ICK, in his *QST* design of May 1989 [8], but a number of modifications were made to 'Anglicise' the design. The transmitter used conventional analogue NBFM to carry the voice signal and direct sequence modulation to spread the carrier. The receiver consisted of a wideband preamplifier, a de-spreading circuit and a conventional 435MHz FM receiver to demodulate the despread carrier. (**Fig 11**, and [9]).

HISTORIC TRANSMISSIONS

PROLONGED AND EXHAUSTIVE bench testing was followed by what is believed to be the first UK amateur Spread Spectrum transmissions. these were first attempted on 19 January 1992. The transmitter was sited on a hill overlooking Yeovil, Somerset, and the Spread Spectrum receiver was located at the 'laboratory' of Dave Page, G0TIJ. By manual adjustment of the signal locking and tracking clock oscillator the receiver's clock was brought into synchronization with the transmitters and the direct sequence signal was despread and demodulated on the 435MHz FM receiver.

The trial was successful with the receiver remaining locked during the test. As output powers were very low (less than 100mW) the range was limited to around half a mile but the test indicated that the simple Spread Spectrum technology worked. Unfortunately the first UK amateur Spread Spectrum test had to be prematurely terminated as both the battery pack voltage and the rain started to fall!

SIGNIFICANT DEVELOPMENTS

AFTER THE INITIAL EUPHORIA it was decided that the best way forward was to incorporate some additional features into a new design. This would use digital modulation to transmit voice and require no operator intervention to gain and maintain lock. The current system uses 16kbits^{-1} delta modulated digital speech to digitally code-modify the pseudo-random spreading code in the transmitter.

The receiver synchronises and tracks an incoming direct sequence signal using a delay-locked loop (as previously discussed) and the narrowband despread signal (with digital voice modulation impressed on it) is digitally demodulated to give the analogue voice output. This system is currently operating at low powers in a laboratory set-up and full field trials are planned. Since the signal is totally digital it will be necessary for regulatory reasons (as with the first system) to announce the transmission in clear voice (ie FM) on the centre frequency before and after Spread Spectrum test transmissions.

TO THE FUTURE

PERHAPS WE CAN LOOK forward to all UK amateurs being able to experiment with this fascinating mode, and its challenging mix of wideband analogue radio frequency techniques and high speed digital design. Radio amateurs could then advance practical Spread Spectrum technology in the same way as great strides were made in packet radio – a true expression of the real aims of amateur radio.

APPENDIX A: PSEUDO-RANDOM CODES AND GENERATION

PSEUDO RANDOM CODES CAN be categorised as being linear or non-linear codes. Linear codes are generated using linear operations (which for binary pseudo-random codes is solely modulo-2 addition or subtraction). This essentially means only EXOR gates are used in the shift register feedback path. A pseudo-random generator which does not use such techniques is termed non-linear. The most commonly used group of pseudo-random sequences used in Spread Spectrum are the maximal linear code sequences (sometimes called M-sequences or pn codes). Maximal codes are the longest codes that a shift register of specified length can produce and have mathematical properties well suited to Spread Spectrum communications.

A maximal shift register pseudo-random generator consists of a shift register with selected outputs being exclusive – ORed and fed back into the shift register input. The circuit goes through a number of states (determined by the bits in the shift register at each clock pulse) before it repeats itself after a set number of clock pulses.

The maximum number of states for a shift register of length m is 2^m, ie for a 10 stage shift register $2^{10} = 1024$ states. However the all-zero state is not allowable as the pseudo-random generator would 'lock-up' as 'exclusively ORing' two logic '0' results in yet another logic '0' at the input.

Therefore a maximal length pseudo-random code generator can produce a pseudo-random sequence 2^m-1 bits long before repeating itself. To obtain a maximal sequence the correct shift register outputs (tap points) must be found. These could be found by experimentation but this would be very time consuming! Fortunately, tables of feedback connections are available [3]. A 10 stage (ie 10 flip flop) shift register can produce a maximal code of length $2^{10} - 1 = 1023$ bits long (bits are known as 'Chips' in Spread Spectrum terminology).

The feedback tap points may be taken from the following stages: [10,3], [10,8,3,2], [10,4,3,1], [10,8,5,1], [10,8,5,4], [10,9,4,1], [10,8,4,3], [10,5,3,2], [10,5,2,1] and [10,9,4,2]. As the simplest circuit implementation is often desired, the first option of tapping the tenth and third stages is selected (see Fig 4). To avoid the all zero – lock up problem, inverting stages are inserted at the shift register input and output.

When the shift register is switched on, a reset pulse is initiated. This pulse initiates all shift register outputs to logic '0', this would normally lock up the pseudo-random sequence generator. However the input inverter injects a logic '1' so that the maximal sequence can commence. The output inverter ensures that maximal code output is inverted negating the effect of the 'anti-lock-up' inverter at the input. The maximal code is also available at the output (A) of the modulo –2 adder, but the second inverter output is normally used to permit direct drive of the DBM in a ds system. Such a maximal linear pseudo-random code generator can be built from as little as two TTL logic family integrated circuits.

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FURTHER READING

Spread Spectrum Systems Second Edition, Robert C Dixon, Wiley Interscience, ISBN 0-471-88309-3.

The ARRL Spread Spectrum Sourcebook, Edited by André Kesteloot, N4ICK, and Charles Hutchinson, K8CH, ARRL, ISBN 0-87259-317-7.

Spread Spectrum Communications Vol 1, 2 and 3, Marvin K Simon, Jim K Omura, Robert A Scholtz and Barry K Levitt, Computer Science Press, ISBN 0-88175-017-4 (Set).

Coherent Spread Spectrum Systems, Jack K Holmes, Wiley Interscience, ISBN 0-471-03301-4.

The books by Dixon and Kesteloot are the best for an introduction to the theory and practical implementation of Spread Spectrum (especially Kesteloot). The other two books are considerably more mathematical in their treatment of the subject.

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